Precision B Lifetimes and B Mixing in CDF

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The CDF detector has collected between February 2002 and February 2004 a *physics quality* sample of about 270 pb^{-1}. Three topics under study, using the entire sample or part thereof, are covered here: exclusive decays lifetimes, time dependent polarization amplitudes of $B_d \to J/\psi K^{*0}$ and $B_s \to J/\psi\phi$ decays, and mixing in B_d decays.

1. INTRODUCTION

The upgraded Collider Detector at Fermilab (CDF) at the $p\bar{p}$ Tevatron collider is back in operation since March 2001, beginning a new period of data taking (Run II). A detailed description of the upgraded detector can be found elsewhere [1]. New vertexing, triggering and particle identification capabilities have been added enhancing the potentialities of the B physics program.

2. TRIGGERS

Three different triggers are currently used at CDF for Beauty and Charm Physics. The *di-muon trigger* selects muon pairs with the transverse momentum of the muons larger than 1.5 GeV/c. This provides $B \to J/\psi X$ modes down to very low transverse momentum of the J/ψ. The *lepton + displaced track trigger* selects one lepton (muon or electron) of transverse momentum larger than 4 GeV/c and one displaced track with transverse momentum larger than 2 GeV/c and 120 μm $< d_0 <$ 1 cm. This provides large and clean samples of semileptonic modes. The *hadronic trigger* selects track pairs with transverse momentum larger than 2 GeV/c and 100 μm $< d_0 <$ 1 cm, providing samples of fully hadronic B decays, like $B_d \to D^-\pi^+$.

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3. PRECISION B LIFETIMES

In CDF Run I the lifetimes of B^+, B_d and B_s mesons were measured using fully reconstructed decay modes with a $J/\psi \to \mu^+\mu^-$ in the final state [2]. The lifetime of the B_s meson is still poorly measured, making it difficult to confront experimental values of lifetime ratios with theory predictions. Measuring the B_s meson lifetime in the decay into a state of definite CP is also important because theory predicts a lifetime difference between the two B_s CP eigenstates, which can be extracted by combining lifetime measurements with angular analysis.

Three B decays have been used to extract the lifetimes:

$$B^+ \to J/\psi K^+,\ J/\psi \to \mu^+\mu^-$$
$$B_d \to J/\psi K^{*0},\ J/\psi \to \mu^+\mu^-,\ K^{*0} \to K^+\pi^-$$
$$B_s \to J/\psi\phi,\ J/\psi \to \mu^+\mu^-,\ \phi \to K^+K^-$$

They are based on the sample accumulated via *di-muon trigger*, with an integrated luminosity of 240 pb^{-1}. The decay selection relies on kinematics, vertex quality and mass window cuts, all chosen to minimize the uncertainty of the extracted lifetime. For each B decay we use an unbinned likelihood method to extract the lifetimes, fitting simultaneously the measured invariant mass and the reconstructed proper decay length. The mass term is fitted with a Gaussian for signal and a first order polynomial for the background, whereas the proper decay length term is more complicated and consists of: positively lived exponential for signal, δ-function for prompt background, and three additional exponential tails for other sources of background. All of these components are convoluted on an event-by-event basis with a resolution function, which is assumed to be Gaussian. In total the likelihood is minimized with respect to 12 parameters (3 from the mass fit, 8 from the proper decay length fit and one that accounts for the fraction of signal events in the sample). The projections of the fit for B^+ can be seen in Figures 1 and 2. The final results for the three decays are summarized in Table 1.

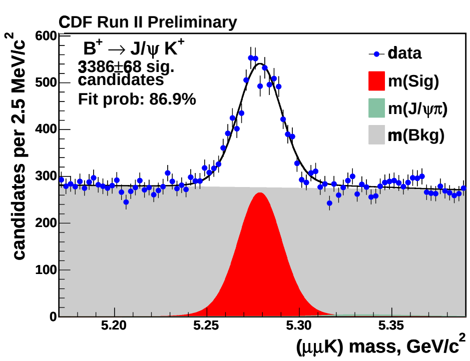

Figure 1. Invariant mass spectrum of the $B_d \to J/\psi K^+$ candidates. The result of the maximum likelihood fit is overlaid.

We also present a measurement of the lifetime of the Λ_B b-baryon in the decay $\Lambda_B \to J/\psi\Lambda$, where $J/\psi \to \mu^+\mu^-$ and $\Lambda \to p^+\pi^-$. This analysis has been done based on the *di-muon trigger* with an integrated luminosity of 65 pb^{-1} and represents the first Λ_B lifetime measurement in a fully reconstructed mode. Furthermore, currently the only operating machine at which they are produced is the Tevatron.

The lifetime measurement is performed with an unbinned maximum likelihood fit to the proper decay length distribution in the signal and sideband regions. From a binned likelihood fit of the Λ_B invariant mass we define the signal region events as those within 3σ of the fitted mean mass, whereas the background region events are those in the sidebands starting at 6σ away from the mean mass. The result is quoted in Table 1.

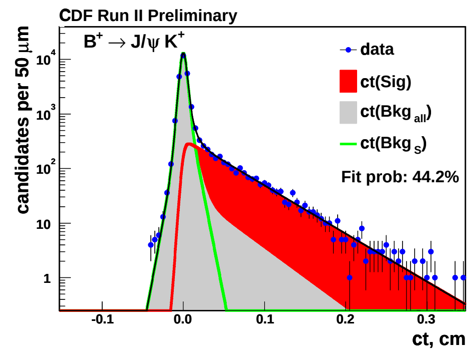

Figure 2. The proper decay length distribution of all $B_d \to J/\psi K^+$ candidates passing the selection cuts. The result of the maximum likelihood fit is overlaid.

4. POLARIZATION AMPLITUDES

The measurement of transversity amplitudes for $B_s \to J/\psi\phi$ and $B_d \to J/\psi K^{*0}$ is of interest for many reasons. One of the important goals in Run II is to measure the lifetime difference $\Delta\Gamma_s$ between the CP eigenstates $B_{s,H}$ and $B_{s,L}$. These two states decay to distinct angular distributions. As has been shown theoretically [3], an angular analysis based on transversity variables combined with a lifetime measurement permits one to separate the CP even and CP odd final states of $B_s \to J/\psi\phi$ and hence determine the lifetime difference. The similar angular measurement $B_d \to J/\psi K^{*0}$ may be compared with those from B factories [4] and the most recent ones [5,6] which will ensure the accuracy of the B_s study.

Based on the *di-muon trigger*, the analyzed sample corresponds to 260 pb^{-1} and about 1150 B_d and 200 B_s candidates pass the selection cuts. An unbinned likelihood fit is performed in terms of the mass, proper decay length and transver-

Table 1
Lifetime results compared to the world average, and lifetime ratios.

B meson	This, ps	PDG'03, ps	τ_B/τ_{B_d}
$B+$	$1.662 \pm 0.033 \pm 0.008$	1.671 ± 0.018	$1.080 \pm 0.042(tot.)$
B_d	$1.539 \pm 0.051 \pm 0.008$	1.537 ± 0.015	—
B_s	$1.369 \pm 0.100^{+0.008}_{-0.010}$	1.461 ± 0.057	$0.890 \pm 0.072(tot.)$
Λ_B	$1.25 \pm 0.26 \pm 0.14$	1.229 ± 0.080	$0.806 \pm 0.192(tot.)$

sity angular variables, described in [9], simultaneously. The detector acceptance and efficiency sculpt the angular distributions significantly. We have corrected for this sculpting by including extra normalization terms in the likelihood function which are determined by Monte Carlo studies. The final results for the amplitudes of both decays are listed in Table 2 and represented in Figures 3 and 4.

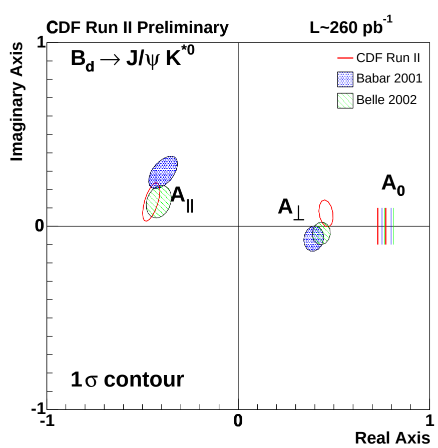

Figure 3. Argand plot showing a comparison of the B_d transversity amplitudes obtained in this analysis with those from BaBar [7] and Belle [8].

For B_s we can extract the CP even and CP odd lifetimes from the unbinned likelihood fit, and therefore $\Delta\Gamma/\Gamma$. The projection of the lifetime fit can be seen in Figure 5. Assuming no

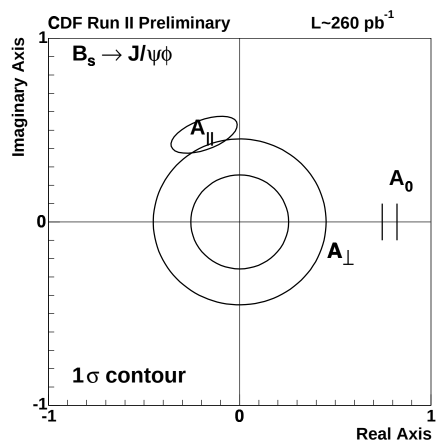

Figure 4. Argand diagram of the transversity amplitudes of B_s.

constraints we obtain

$$\tau_L = 1.05^{+0.16}_{-0.13} \pm 0.02 \text{ ps}^{-1}$$
$$\tau_H = 2.07^{+0.58}_{-0.46} \pm 0.03 \text{ ps}^{-1}$$
$$\Delta\Gamma/\Gamma = 0.65^{+0.25}_{-0.33} \pm 0.01 \text{ ps}^{-1}$$

5. B MIXING

The mixing and CP violation parameters of B mesons are currently the focus of much attention for pinning down the CKM matrix, and perhaps exposing new physics beyond the Standard Model. We are not in a position to make physically interesting measurements of parameters like Δm_d. It is crucially important, however, that we

Table 2
Polarization amplitudes results of $B_s \to J/\psi\phi$ and $B_d \to J/\psi K^{*0}$.

	B_d	B_s
A_0	0.750 ± 0.017 ± 0.012	0.784 ± 0.039 ± 0.007
$\|A_{\parallel}\|$	0.473 ± 0.034 ± 0.006	0.510 ± 0.082 ± 0.013
$\|A_{\perp}\|$	0.464 ± 0.035 ± 0.007	0.354 ± 0.098 ± 0.003
$arg(A_{\parallel})$	2.86 ± 0.22 ± 0.07	1.94 ± 0.36 ± 0.03
$arg(A_{\perp})$	0.15 ± 0.15 ± 0.04	—

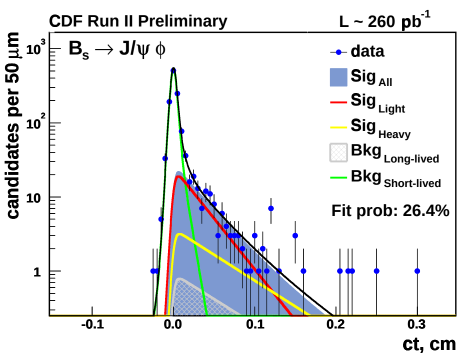

Figure 5. Projection of the result of the unbinned likelihood fit onto the data for $B_s \to J/\psi\phi$ proper decay length.

measure well known parameters like Δm_d to establish the credibility and capability of the CDF detector and the techniques which we wish to apply on future tagging measurements like Δm_s.

To determine Δm_d the flavor of the B meson at production and at decay time need to be known. The flavor at decay is provided by the decay products of the B meson. The flavor of the B meson at production time was inferred using the Same-Side Tagger (SST) which was developed in CDF Run I [10]. The SST relies on the existing charge correlation between a b quark and the closest particle in the fragmentation string.

The oscillation frequency Δm_d has been measured in both fully reconstructed and semileptonic decays. In the first case several neutral decays have been analyzed [11], with the names and the yields quoted in Table 3.

Table 3
Fully reconstructed neutral decay modes yields.

Decay	Yield
$B_d \to J/\psi K^{*0}$	1405 ± 45
$B_d \to D^-\pi^+$	5545 ± 100
$B_d \to D^{*-}\pi^+$	1722 ± 51
$B_d \to D^{*-}\pi^+\pi^+\pi^-$	1253 ± 53
$B_d \to D^-\pi^+\pi^+\pi^-$	2650 ± 78

In Figure 6 we can see the invariant mass of $B_d \to D^-\pi^+$ candidates with the binned fit overlaid. Figure 7 shows the measured time dependent asymmetry for $B_d \to D^{*-}\pi^+$. From the combined fit of the aforementioned decays we obtain the following values for the oscillation frequency Δm_d and the *tagging effectiveness* ϵD^2,

$$\Delta m_d = (0.526 \pm 0.056(stat.) \pm 0.005(syst.))\ \text{ps}^{-1}$$
$$\epsilon D^2(B_d) = (1.00 \pm 0.35(stat.) \pm 0.06(syst.))\ \%$$

In the semileptonic decays a $B \to lD^{(*)}$ sample obtained from the *lepton + displaced track trigger* has been used. This study has a larger yield when compared with respect to the fully reconstructed but it has to deal with 'sample composition' issues. In principle we want to measure B_d mixing through $B_d \to l^+D^-$ decays, and therefore a l^+D^- sample is the starting point for such goal, but this sample will in fact *not* be a pure B_d sample. Our ability to reconstruct final states

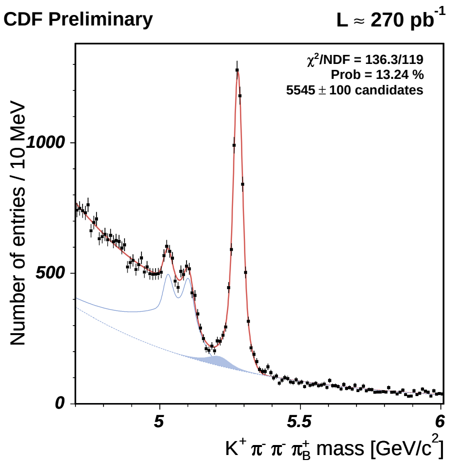

Figure 6. Invariant mass spectrum of the $B_d \to D^-\pi^+$ candidates. The result of the fit is overlaid (red line). The blue shaded histogram corresponds to the Cabibbo suppressed decays $B_d \to D^-K^+$.

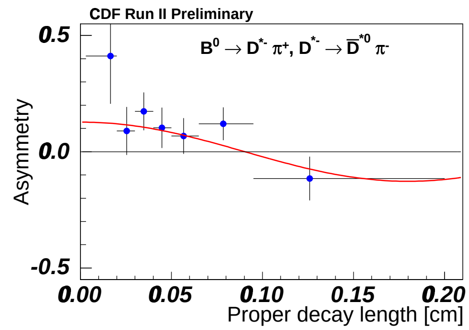

Figure 7. Measured asymmetry as a function of the proper decay length for the $B_d \to D^{*-}\pi^+$ candidates. The simultaneous oscillation fit is overlaid.

is not perfect due to cross-talk between B_d and B^+ decays. Three B meson final states are reconstructed in this analysis, and they nominally correspond to the decays:

$$B_d \to \nu l^+ D^{*-},\ D^{*-} \to \bar{D}^0\pi^-,\ \bar{D}^0 \to K^+\pi-$$
$$B_d \to \nu l^+ D^-,\ D^- \to K^+\pi^-\pi^-$$
$$B^+ \to \nu l^+ \bar{D}^0,\ \bar{D}^0 \to K^+\pi^-$$

In this case a combination of all the taggers currently available at CDF has been done. That includes SST as in the fully reconstructed decays and Opposite-Side taggers: Soft Muon Tagger (SMT) and Jet Charge Tagger (JQT), described in some detail at the end of this section. The JQT is divided in two categories, depending upon the finding of a secondary vertex.

We need a single tagging decision per candidate, therefore we have to agree on which tag decision to assign. The Opposite-Side taggers are applied starting with the one that has higher dilution: first the SMT, if it fails then the JQT with a secondary vertex, and finally the JQT with no secondary vertex. At the end we have several possible cases: only SST; only OST; SST and OST when the tagging decisions agree; SST and OST when the tagging decisions disagree.

A binned χ^2 function is formed to fit simultaneously Δm_d, five different dilutions (SST B^+, SST B_d, SMT, JQT with secondary vertex and JQT without secondary vertex), where the dilution is defined as $2f - 1$, with f the fraction of correctly tagged B mesons. The asymmetry fit does not only depend upon those six parameters of direct interest, but also on 7 more parameters, described in [12].

Figure 8 shows the fit results in the case were both SST and SMT decisions agree. When combining all the cases, we obtain the following values for Δm_d and $\epsilon D^2(B_d)$,

$$\Delta m_d = (0.536 \pm 0.037(stat.) \pm 0.017(syst.))\ \text{ps}^{-1}$$
$$\text{Combined } \epsilon D^2(B_d) = (1.820 \pm 0.115(total.))\ \%$$

Taggers based on the Opposite-Side properties are also under development at CDF, following the results obtained in Run I. Using a sample based on the *lepton + displaced track trigger* we test both Soft Muon and Jet Charge Taggers. Such sample is rich in statistics (more than one million semileptonic b events) and the lepton charge pro-

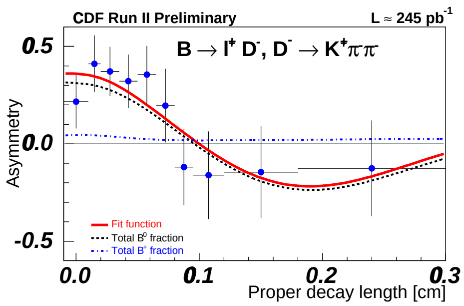

Figure 8. Measured asymmetry with the fit results superimposed (solid red line) for the l^+D^- signature when candidates are tagged with both SST and SMT, and the tagging decisions agree. The contributions of B_d (black dashed line) and B^+ (blue dot-dashed line) decays are also shown.

vides the signal B flavor at decay. Since the signal B is not even partially reconstructed, to get a pure $b\bar{b}$ sample we do the following: $c\bar{c}$ events are removed by requiring the invariant mass of the lepton and the *displaced track* in each event to be $2 < M_{lt} < 4$ GeV/c^2. The non-heavy flavor background is suppressed forming the signed impact parameter δ_{svt} for each lepton-*displaced track* candidate. It has the same magnitude as the impact parameter of the *displaced track* d_0^{svt} and its sign is

$$sign(d_0^{svt} \cdot (sin\Phi_0 cos\phi_0^{svt} - sin\phi_0^{svt} cos\Phi_0)) \qquad (1)$$

where Φ_0 is computed for the total momentum vector of the lepton and the *displaced track*. δ_{svt} is expected to be distributed symetrically around $\delta = 0$ for non-heavy flavor events. To suppress background all distributions are δ_{svt}-subtracted, i.e. $\delta_{svt} < 0$ defines the background.

The Soft Muon Tagger looks for events with a $B \to \mu X$ decay in the Opposite-Side. This is a high purity tagger but quite inefficient, given the small branching ratio of decays with a muon in the final state, BR($B \to \mu X$) ~ 10 %. The current performance for this tagger is

$$\epsilon D^2 = (0.660 \pm 0.193(stat.))\ \%$$

The Jet Charge Tagger looks for the jet coming from the Opposite-Side b and then calculates the weighted average charge Q_{jet} of the tracks from the jet. This tagger has smaller purity but on the other hand it is very efficient, since whenever the Opposite-Side b is in the acceptance volume it will almost always give a jet. In this case the performance is

$$\epsilon D^2 = (0.715 \pm 0.027(stat.))\ \%$$

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